

Search for Highly Ionizing Particles at the Fermilab Proton-Antiproton Collider

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In a search for highly ionizing particles produced in $p\bar{p}$ collisions at $\sqrt{s}=1800$ GeV, polycarbonate and CR-39 plastic track detectors were exposed to an integrated luminosity of $\sim 5 \times 10^{32} \text{ cm}^{-2}$, and UG-5 glass detectors were exposed inside the vacuum system to look for short-range particles. No highly ionizing particles other than hadronically produced spallation recoils were detected.

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Several types of hypothetical particles with high ionization rates in matter have been the subjects of theoretical discussion. These range from the structureless point magnetic monopole of Dirac¹ to the highly structured magnetic monopoles² and "balls" of electric charge³⁻⁵ predicted in non-Abelian gauge theories. Because of form-factor suppression,⁶ the cross section for producing objects with extended structure in $p\bar{p}$ collisions may be impossibly low. Therefore, in discussing our present search, we will focus attention on its implications for pointlike magnetic monopoles. Their magnetic charge is an integral multiple n of $g_0 = \hbar c/2e = 68.5e$, and their ionization rate is very high⁷:

$$-(dE/dx)_m \approx (g\beta/e)^2 (dE/dx)_e, \text{ for } \beta \gg \alpha,$$

$$-(dE/dx)_m \approx K\beta, \text{ for } 3 \times 10^{-4} < \beta < 0.2,$$

where $-(dE/dx)_e$ is the energy loss rate for a proton, and $K \approx 33n^2 \text{ GeV/cm}$ for plastic, $K \approx 124n^2 \text{ GeV/cm}$ for Fe. In contrast to the case with non-Abelian gauge monopoles, the mass of a point monopole is unspecified. Consequently, monopoles have been sought in cosmic rays and at each accelerator that opens up a new mass regime.⁸

We exposed three types of track-etch detectors at the D0 collision region during a run at the Fermilab collider at $\sqrt{s}=1800$ GeV. The horizontal lines in Fig. 1 show the ranges of sensitivity thresholds for the three types of detectors. The intersections of the lines with the curves of $Q/\beta e$ (equivalent charge/velocity) for monopoles with $n=1$ and 2 give the minimum detectable velocity for those monopoles. Table I contains information on the processing, response, and sensitivity of the detectors to background radiation and to monopoles. Ionization dose (row 8 of Table I) is not a problem for these detectors. What limits their applicability in a hadron collider is the production of short tracks, typically a few micrometers in length, due to highly ionizing fragments of hadronic

interactions in the detector and beam pipe (row 9). For each detector, in this search the observed density of etch pits due to such tracks (row 10) was well below the maximum tolerable density of $\approx 10^8/\text{cm}^2$. For the etching conditions used (rows 2 and 3), the minimum detectable values of $Q/\beta e$ are given in rows 4 and 5 for zenith angles of 0° and 45° to the detector surfaces. The minimum velocities for detection of a normally incident monopole with $n=1$ and $n=2$ are given in rows 6 and 7, respectively.

Our estimate of $5 \times 10^{32} \text{ cm}^2$ for the integrated luminosity at D0 is obtained⁹ by scaling of the luminosity measured at the CDF detector by the ratio ($= \frac{1}{70}$) of values of the machine parameter β at B0 and D0 and also by the fraction of coasts ($\approx \frac{1}{2}$) with proton-antiproton bunches that would collide at D0 as well as at B0.

The signature of a monopole would consist of a chain of connected etch-pit pairs in several successive sheets,

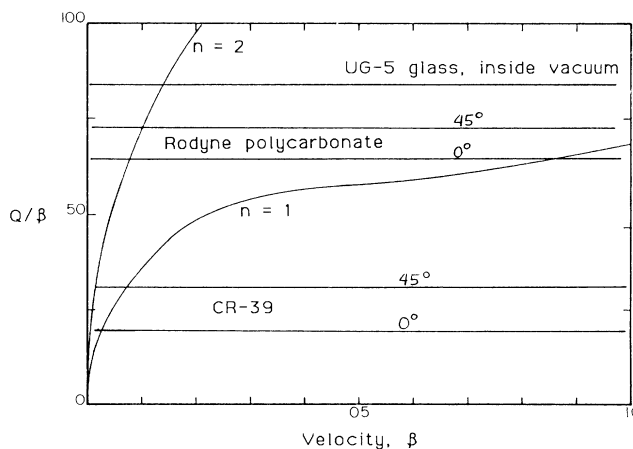


FIG. 1. Effective value of Q/β , in terms of ionization rate, for monopoles with magnetic charge $g/g_0=1$ and 2, and sensitivity thresholds for the detectors used.

TABLE I. Processing, response, and sensitivity of detectors to background radiation and to monopoles.

	CR-39	Rodyne	UG-5
Solid angle ($\Omega/4\pi$)	0.7	0.7	≈ 0.18
Etchant	6.25N NaOH	6.25N NaOH	49% HBF ₄
Final/initial thickness	0.3	0.4	0.84
$(Q/\beta)_{\min}$ for $\theta=0^\circ$	20	65	84
$(Q/\beta)_{\min}$ for $\theta=45^\circ$	31	73	84
Minimum detectable β for			
$n=1$	0.025	0.86	Undetectable
$n=2$	0.006	0.076	0.14
Dose limit (Mrad)	2	200	1000
Etch pits/hadron due to spallation	10^{-4}	4×10^{-6}	2×10^{-7}
Density of detected etch pits (cm^{-2})	6×10^6	2×10^5	10^5

indicating a particle with ionization rate decreasing as it slowed. Our accuracy of ≈ 10 mrad in track angle and ≈ 500 μm in alignment of adjacent sheets results in a negligibly small probability of accidental coincidence of unrelated background tracks, even at far higher integrated luminosity than can be attained at the Fermilab collider. If a candidate monopole track were detected, we could locate to within ≈ 1 mm the position of the track of an oppositely directed antimonopole on the opposite side of the vacuum pipe.

The two types of plastic detectors,¹⁰ 700- μm CR-39 and 100- μm Rodyne polycarbonate (similar to Lexan), were deployed in a cylindrical geometry around the 150- μm -thick steel beam pipe. The inner sheet was Rodyne, the next five were CR-39, and the outer three were Rodyne. The 900- μm UG-5 glass sheets¹¹ were kept inside the vacuum system during the entire run. They subtended about one-fourth the solid angle of the plastic sheets.

The etched glass sheets were scanned microscopically for etch pits longer than ≈ 100 μm on the surface nearer to the beam, with the idea of looking for matches of such etch pits on the far surface. No such pairs were found.

After etching the plastic sheets, we scanned them by an ammonia gas technique,¹⁰ which registers the location of any hole etched through a sheet by producing a blue spot on a sheet of chemically treated paper in contact with the sheet. The criterion for formation of a hole due to an etch-pit pair connected point to point is that

$$(s_{\text{top}} + s_{\text{bottom}})\cos\theta > 2H_0/(H_0 - H_f),$$

where $s \equiv v_T/v_G$, the ratio of track-etching rate to general etching rate, and H_0 and H_f are pre- and post-etch thickness. The maximum zenith angle θ for hole production, i.e., acceptance, depends on s_{top} and s_{bottom} , and thus on ionization rate. On the basis of etching of a small test sheet, the sheets were etched down to a thickness H_f slightly larger than that at which a large density of holes due to spallation recoils would show up (≈ 200

μm in CR-39).

Table II shows the number of etched holes found in the ammonia scan of the plastic detectors, excluding small regions of high hole density in CR-39 corresponding to unusually small values of H_f . For four reasons we attribute all of the etched holes to tracks of highly ionizing nuclear fragments of hadronic interactions in the beam pipe and in the plastic sheets. (1) The highest density of holes was in the inner Rodyne layer, adjacent to the steel pipe. In the outer three Rodyne layers the density of holes was much lower and was the same in each layer. These results are consistent with the short range of spallation recoils and with the higher cross section for production of such recoils in the Fe of the beam pipe than in the low- Z plastic sheets. (2) Examination of sheets adjacent to detected holes revealed no holes in the corresponding locations, which supports the view that the tracks were produced in the Fe pipe and plastic sheets by short-range particles. (3) Despite the higher sensitivity of CR-39 than of Rodyne, the density of holes was much higher in the latter than in the former material. This is a natural consequence of a spallation origin,

TABLE II. Results of search for correlated holes.

Detector	No. of holes	No. that follow into adjacent sheet
Rodyne	1968	0
CR-39	1 ^a	0
CR-39	0 ^a	0
CR-39	0 ^a	0
CR-39	2 ^a	0
CR-39	0 ^a	0
Rodyne	97	0
Rodyne	107	0
Rodyne	106	0

^aThese numbers apply only to holes in portions of CR-39 sheets thicker than ≈ 200 μm after etching.

since the range distribution of spallation recoils falls off very steeply with range, and the CR-39 sheets are 7 times as thick as the Rodyne sheets. If any of the holes were due to monopoles or to highly charged objects originating in a $p\bar{p}$ collision, at least some of them should have produced etched holes in more than one successive sheet. (4) The three holes in the CR-39 sheets seemed more likely candidates for exotic events than the holes in the Rodyne because of the greater thickness of the CR-39 and the requirement that the range of the particles had to be at least equal to $700\text{ }\mu\text{m}$ if they originated outside the sheets (or at least equal to $200\text{ }\mu\text{m}$, the post-etch sheet thickness, if they originated inside a sheet as a spallation event). We used a Leitz Ortholux microscope to measure the dimensions of the connected conical etch-pits comprising the holes in CR-39. We found that all were due to particles for which the ionization rate increased as they slowed, in contrast to the ionization rate of a monopole, which would decrease as it slows. One hole was due to a $\approx 200\text{-MeV}$ beryllium fragment; the other two were due to $\approx 40\text{-MeV}$ helium fragments. This number is consistent with the calculated¹² rate of production of spallation recoil nuclei with range $> 200\text{ }\mu\text{m}$ (the post-etch sheet thickness) produced inside the CR-39 sheets.

Taking into account the integrated luminosity and the solid angle for 100% detection efficiency from Table I, we find an upper limit (90% confidence level) of $2.8 \times 10^{-32}\text{ cm}^2$ for production of magnetic monopoles with $n \geq 1$ and mass less than about 800 GeV .

Figure 2 compares this upper limit with limits obtained in previous searches at accelerators. The dashed lines refer to indirect searches, in which monopoles were sought not in flight but subsequent to their presumed extraction and acceleration from matter in which it was

hoped they had come to rest and been trapped. The solid lines refer to direct searches for tracks in plastic detectors or nuclear emulsion. Whenever possible, we have corrected the limits of other authors if they did not properly take into account solid angles or detection efficiencies. We point out that in the searches at CERN ISR,¹³ DESY PETRA,¹⁶ and CERN SPS,¹⁷ Kapton foils were used for some or all of the detectors. Kapton is a much less sensitive detector²¹ than Rodyne and CR-39, and the authors of Refs. 13 to 17 have given either calibration data nor quantitative discussion of the ionization rate for which holes would have been produced in their experiments. Furthermore, in some of the experiments, Kapton was used inside the vacuum system. Studies in our laboratory have shown that, in general, oxygen plays an essential role in track formation in plastic track detectors, and that these detectors lose sensitivity when kept in vacuum.²² We are therefore doubtful of the validity of the limits based on Kapton results, at least for monopoles with $n=1$. We used UG-5 glass inside the vacuum system because its sensitivity does not depend on oxygen partial pressure.²²

Figure 3 shows the limits normalized to pointlike interaction cross sections and attempts to account for the more efficient conversion of beam energy into new particles at e^+e^- colliders than at hadron colliders. The dimensionless ratio R is the cross section normalized to the Drell-Yan cross section for muon-pair production multiplied by $(g/e)^2$. For e^+e^- annihilation the normalization cross section is $\sigma_0 = (g/e)^2(4\pi\alpha^2/3s)$, where the coupling at the monopole vertex is approximated by $(g/e)^2$. For $p\bar{p}$ collisions we calculate using the differential-cross-section data for massive virtual-photon production, which exhibits scaling and falls off exponentially with $x \equiv 2M_m/\sqrt{s}$.²³ To determine the normalization

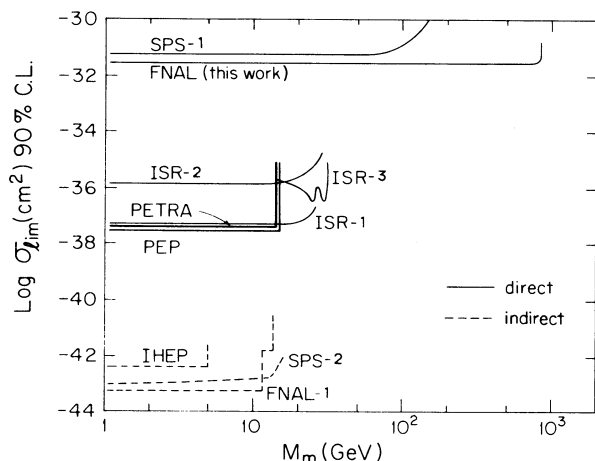


FIG. 2. Upper limits on monopole production cross section. References are as follows: PEP, Ref. 10; ISR-1, Ref. 13; ISR-2, Ref. 14; ISR-3, Ref. 15; PETRA, Ref. 16; SPS-1, Ref. 17; SPS-2, Ref. 18; IHEP, Ref. 19; FNAL-1, Ref. 20.

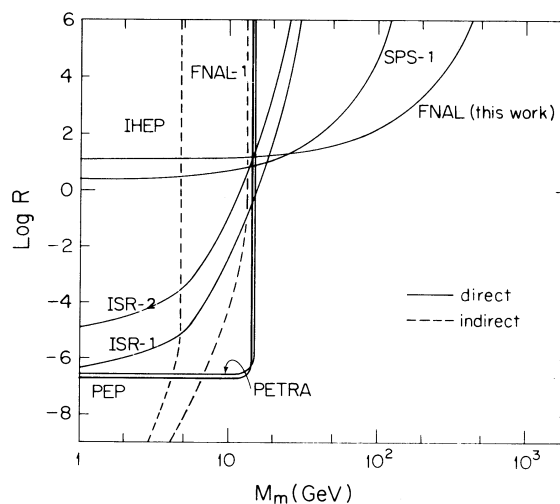


FIG. 3. Upper limits on normalized production cross sections (see text).

cross section for production of a monopole pair with total mass $> 2M_m$, we integrate over masses greater than $2M_2$ and over the rapidity interval $[-0.5, 0.5]$, and multiply by $(g/e)^2$. The normalization cross section is intended to be a rough point of reference for production of magnetic monopole pairs via the electromagnetic process. This estimate is conservative: Higher-order diagrams with more than one virtual photon in the intermediate state will also contribute, and production via gluon-gluon fusion may be more likely still.²⁴

We conclude from Fig. 3 that, although the present search provides the best cross-section limit for monopole mass $\gtrsim 20$ GeV, the ratio R is much greater than unity, which implies that the existence of monopoles with such mass has not been ruled out in experiments to date. Without any design changes, the limiting density of background spallation events of $\approx 10^8/\text{cm}^2$ in the CR-39 detectors would be reached at an integrated luminosity of $\approx 10^{34} \text{ cm}^2$, a factor ≈ 20 greater than attained in the present experiment. We hope to attain such an integrated luminosity in the next collider run at Fermilab, which would provide a more definitive test of production of monopoles via a Drell-Yan process.

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